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Subthreshold mobility in AlGaN/GaN HEMTs

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***Abstract*— Electron mobility of AlGaN/GaN HEMTs is studied using a gate admittance based technique. This analysis extends to electron densities as low as 4×10^{10}cm^{-2} with good accuracy. Zero lateral electric field is applied, in contrast to conventional methods. At these low electron densities the mobility can be a factor of ~ 50 less than that in the on-state. We reveal a regime at low electron densities where the screening of the 2DEG becomes negligible causing the mobility to be independent of electron concentration, suggesting percolative transport. This region defines the rate at which the channel depletes and is a strong indicator of epitaxial control of impurities in the GaN channel.**

***Index Terms*— AlGaN/GaN HEMT, series resistance, 2DEG mobility.**

I. Introduction

HIGH electron mobility and carrier density in AlGaN-GaN heterojunction transistors make them excellent candidates for high power switching applications. However it has long been known that as a field-effect-transistor is switched off and the channel depleted the mobility can vastly decrease [1]. This behavior is due to a reduced screening of the charges that cause Coulomb-scattering and impacts the transconductance putting a limit on the rate that the channel can be depleted. Consequently the behavior of mobility in switching is an important parameter for characterization and optimization of a power device.

Electron mobility, μ is often measured using the field effect (FE) mobility technique this uses the transconductance and differs significantly from the effective mobility [2]. However the conductance mobility should be used [3], which is derived from an expression for the current, I_D through the device of width W and gate length L_G,

$$I_D = \frac{W n_i q \mu V_D}{L_G} \tag{1}$$

where the voltage drop along the intrinsic device channel is V_D. This expression assumes that there is negligible diffusion current along the channel, which is only true far from threshold when $(V_G - V_T) \gg V_D$[2]. When finding the charge per unit area, $n_i q$, an integral of the capacitance-gate voltage (C-V$_G$) curve can be used leading to

$$\mu = \frac{I_D L}{W V_D \int_{-\infty}^{V_G} C dV_G}. \tag{2}$$

This normally requires separate I$_D$-V$_G$ and C-V$_G$ measurements and if there is any instability in the threshold voltage (V_T) large error will exist for the mobility near pinch off. Thus this expression is often simplified for measurement in the linear region to

$$\mu = \frac{dI_D}{dV_D}\frac{L_G}{W}\frac{1}{C_b(V_G - V_T)}. \tag{3}$$

This assumes a step-like C-V$_G$ characteristic from zero to the capacitance of the barrier C_b which inevitably is a source of error, particularly at low carrier densities.

While Hall-effect measurements on gated Hall structures are less prone to error, the published studies have not shown mobilities extending to a low electron density region <10^{11} cm^{-2}[4][5][6]. This may be due to the requirement for large magnetic fields if the mobility drops in this regime.

The method employed here has built upon previous work studying the gate admittance of GaN HEMTs [7] and is used here to characterize the mobility in the subthreshold regime. This approach allows accurate extraction of the zero field mobility at much lower electron densities in one voltage sweep, without applying a drain bias, thus avoiding threshold errors and the complication of a diffusion current respectively. At low densities we reveal a new behavior of the mobility for

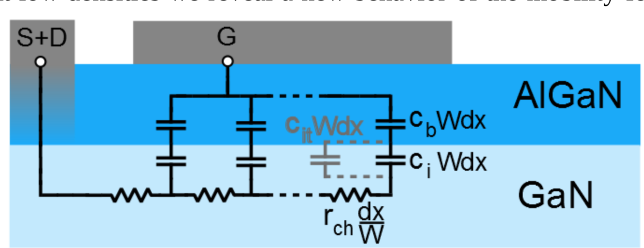

Fig. 1. Equivalent circuit model of fatFET capacitor structure. The device is of length $L = \sum dx$ and width W. r_{ch} is the sheet resistance, c_i is the capacitance per unit area of the 2DEG, c_b is the barrier capacitance per unit area. The capacitance per unit area of interface traps, c_{it} is depicted greyed on the figure, but is not included on the model as it is not the dominant loss mechanism for large gate length devices such as the one considered here.

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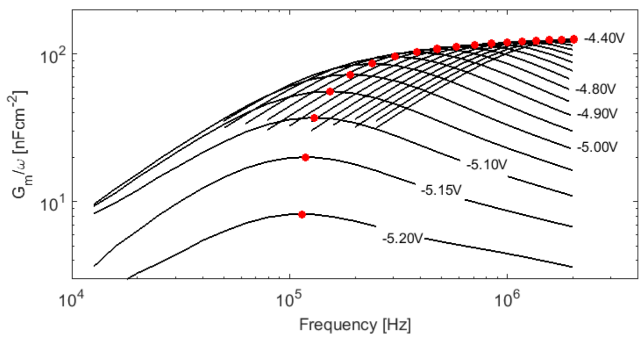


Fig. 2. Measured G_m/ω through gate contact of device A at different gate voltages, peak positions are marked with circles. f_{gc} falls and then becomes constant at -4V, following the behavior of mobility.

GaN devices, where screening of Coulomb-scatterers becomes negligible. Here mobility is independent of carrier density.

II. Method

The frequency dispersion of conductance through the gate contact was studied in order to determine 2DEG mobility. A method of measuring mobility from gate admittance was first discussed by Chow *et al.* [8] but has never been applied to GaN based devices. The method is particularly suited to GaN HEMTs as the highly insulating buffer greatly simplifies the equivalent circuit, and the low interface trap density at the AlGaN/GaN barrier ($\leq 10^{10}$ $eV^{-1}cm^{-2}$ [7]) makes low frequency dispersion small such that accurate n_i can be attained simultaneously. Large fatFET capacitor structures are used with a contact to the 2DEG and another to the gate, this setup means the mobility is measured in a situation where zero lateral electric field is applied. This avoids decrease of the electron mobility in the AlGaN/GaN channel at high lateral electric fields due to inter valley scattering and self-heating effects [9]. The mobility measured on fatFETs applies to the electrons under the gate, in a real device the electron concentration will be higher in the gate to drain region, the influence of field plates will mean concentration and hence the mobility will vary at different positions in the device, all of these effects contribute to device behavior. However a fatFET is still a good approximation of the electric field and concentration under the gate. Edge effects in a real device are small provided t/L_G is small.

The main contribution to dispersion when the gate is biased to subthreshold is an RC circuit produced by the capacitance of the gate stack and the lateral resistance of the long length channel. This produces a peak in the equivalent semiconductor conductance, G_m/ω, which is often misinterpreted as interface traps [7].

An equivalent circuit model of the device is constructed, depicted in Fig. 1. The channel resistance r_{ch} of each element varies as

$$r_{ch} = \frac{1}{\mu n_i q}, \tag{4}$$

where μ is the 2DEG conductance mobility.

The capacitance per-unit-gate-area varies as the series addition of three parts, c_b, the barrier capacitance,

$$c_b = \frac{\varepsilon}{t}, \tag{5}$$

c_{DOS}, the density of states contribution to the 2DEG layer capacitance,

$$c_{DOS} = \frac{qn_i}{2kT/q}, \tag{6}$$

and finally c_{thick}, the contribution to the 2DEG layer capacitance due to the separation of the 2DEG, d_0, from the AlGaN/GaN interface,

$$c_{thick} = \frac{\varepsilon}{d_0}. \tag{7}$$

Where the dielectric constant of the AlGaN barrier is given by ε, the thickness is t, and kT/q is the thermal voltage. The total 2DEG capacitance per unit area c_i is the series-combination of c_{DOS} and c_{thick}. d_0 will slightly decrease with n_i, however it is not a critical parameter and its value is fixed here as 1nm. The free electron density at each gate voltage can be found by integrating the low-frequency C-V_G curve that is obtained simultaneously with G_m/ω, as admittance is measured. The low frequency capacitance has no dispersion due to the distributed resistance under the gate and there is negligible low frequency dispersion due to interface traps. Obtaining the free electron density simultaneously with the conductance means that systematic errors due to threshold instability are avoided.

Using these elements in an equivalent circuit model, mobility can be used as the free parameter in order to fit the model to experiment. This method allows mobility to be studied at very low electron concentrations.

III. Results and Discussion

Three devices were studied, a commercial device and two research devices. The research devices are Schottky contact AlGaN/GaN fatFET capacitor structures connected with source left floating. The gate dimensions were 100µm length and 150µm width. The heterostructures are composed from top down as follows: 2 nm GaN, 27 nm AlGaN, 1nm AlN, 250 nm undoped GaN channel, 0.8 µm carbon doped GaN with $\sim 1 \times 10^{18}$ cm^{-3} carbon content. From here they differ 1.8/4.0 µm compositionally graded AlGaN, 250 nm AlN and the Si substrate (1 mm). These shall be referred to as device A and

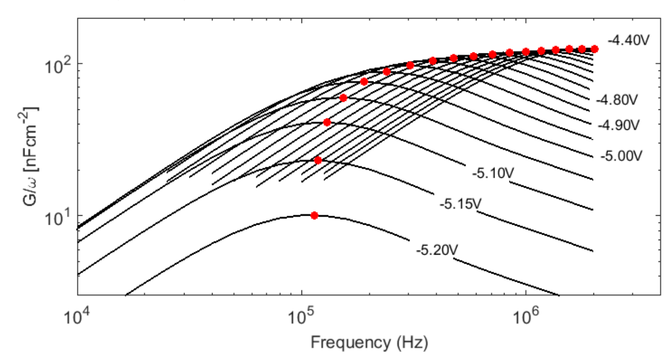


Fig. 3. Modelled G_m/ω through gate contact of device A at different gate voltages, peak positions are marked with circles. f_{gc} has been fitted to measurements in Fig. 2 using mobility as the only free parameter, thus extracting the mobility.

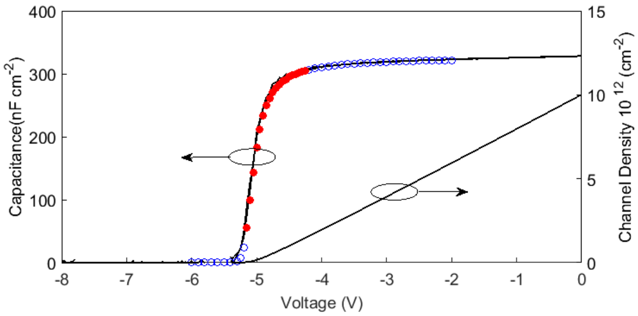


Fig. 4. C-V data of device A. Measured (black line) and modelled (dots) are shown with good agreement. The opaque dots highlight the points where mobility can be extracted. The channel concentration has also been plotted, calculated by integrating the C-V curve.

device B respectively. Device C was a commercial Schottky contact AlGaN/GaN capacitor structure with gate length 500µm and width 200µm. An Agilent E4980A precision LCR meter was used in the frequency range 1 kHz – 2 MHz with AC voltage of 20 mV. A four point probe method was used, corrected for parasitic capacitance. For comparison conductance mobility was determined using a Keithley 4200 parameter analyzer on device A and B, device C was a two contact device and conductance mobility was not measured.

The frequency response of the gated channel is given by [8]

$$f_{gc} = \frac{4}{c r_{ch} L_G^2} \ . \qquad (8)$$

Figure 2 shows the measured G_m/ω dispersion on device A at different gate voltages after DC-leakage has been removed, this is done by fitting the low frequency limit of the conductance and subtracting it. The characteristic frequency, f_{gc}, decreases as the device is switched off, it then becomes constant below -5.1V. In addition to the change in f_{gc} due to reduction in electron concentration there is change due to the decrease in mobility. The equivalent circuit model described in Sec. II, and further explained in [7] is implemented for device A in Fig. 3 and fitted to the measurement using mobility as the parameter. The measured and modelled C-V_G curve at 1kHz is plotted in Fig. 4, showing good agreement. This demonstrates that values taken for n_i are appropriate and we can describe the capacitance well, without the need for interface states. The opaque circles show where the peak response of the gated channel can be measured and thus the mobility extracted. The three devices provide a comparison of how different epitaxy changes the mobility at low channel density, these have been extracted using the same method as explained for device A and plotted in Fig. 5. The device gate length is important when utilizing this technique, and devices must be designed to have a frequency response at measurable frequencies, The higher mobility present in device C means that not such a low electron concentration can be probed for this particular device geometry.

The form of the mobility is dictated by various independent scattering mechanisms. These different contributions have been studied extensively in many 2D materials [1][10][11] and exhibit different dependencies upon electron concentration, n_i and temperature, T. Important mechanisms include acoustic phonon scattering and surface roughness scattering at high electron concentrations [12][13]. At low electron concentrations Coulomb scattering from ionized impurities and charged dislocations becomes important. These two sources of Coulomb scattering increase when there are less electrons present to screen the charges. Ionized centers have a $\mu_I \propto n_i^1$ contribution to mobility [14] whereas charged dislocations have a $\mu_D \propto n_i^{3/2}$contribution [15]. The differences in these contributions stems from a dimensionality difference in the scattering from a charged point or from a line of charge.

The total mobility is the combination of all the different independent mobility limiting mechanisms, which can be approximated using Matthiessen's rule [16]. If one scattering mechanism dominates we can ignore other contributions. This is the case for device A, looking at the power law dependence of the mobility in Fig. 5 we can see that the dominant contribution to mobility is scattering from ionized impurities ($\mu_I \propto n_i^1$) for electron concentrations 4×10^{10} cm^{-2}$< n_i <$ 7×10^{11} cm^{-2}. Devices B and C do not have a clear dominant scattering mechanism, with a slope of 0.56 and 0.58 respectively, which indicates that a combination of scattering mechanisms are competing. Fig. 6 shows the mobility in device C measured at different temperatures. There is a decrease in the slope of 17% as the temperature is increased

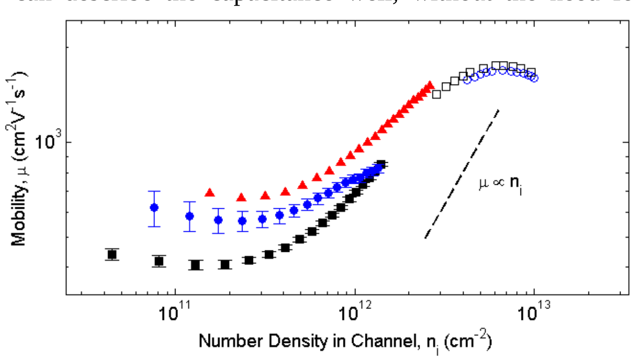


Fig. 5. Extracted mobility for device A (filled squares), device B (filled circles) and device C (filled triangles) demonstrating a reduction as the channel is depleted due to reduced screening. The mobilities reach a constant value as screening of Coulomb-scattering by the 2DEG becomes insignificant. Conductance mobility is also plotted (hollow) for device A and B at higher channel densities.

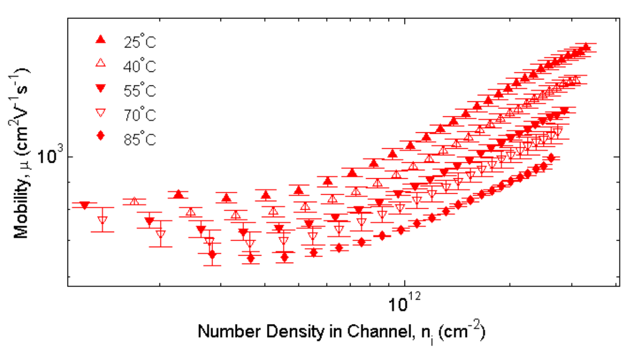


Fig. 6. Extracted mobility for device C at different temperatures. The mobility decreases at all electron concentrations as temperatures rises. At high electron concentrations > 10^{12} cm^{-2} the power law dependence ($\mu \propto n_i^{\gamma}$) changes such that γ decreases by 17% at 85˚C. This indicates an increased contribution of phonon scattering to the mobility.

from 25˚C to 85˚C, this indicates that the contribution to the mobility from phonon scattering is increasing.

At low electron concentrations $n_i < 3\times10^{11}$ a new regime is seen where the scattering is independent of electron concentration. We propose this is due to the electron screening effectively stopping due to an insufficient number of mobile electrons. Scattering is then observed from bare Coulomb potentials. Under these conditions the ground state of the 2DEG would resemble a percolated system, as described by Das Sarma *et al.* [17]. This independence wrt carrier density in sub threshold is also seen in relative spectral noise density (RSND) measurements at low frequency of Si MOSFETs in weak inversion. This is described by Reimbold [18]. The screening of trap occupancy fluctuations can be directly observed by the change in the RSND, it is shown that when the channel capacitance is less than the barrier capacitance the RSND becomes carrier concentration independent, this describes well the same screening situation which causes the mobility to become constant with electron concentration here.

The ac-method presented here is accurate for low electron densities, however the technique is limited to the subthreshold region as shown in Fig. 4 since the response frequency is too high to be measured with a conventional capacitance bridge at high carrier density. The conductance mobility has also been plotted in Fig. 5 for devices A and B. At high electron densities it can be seen to flatten out as phonon scattering becomes the dominant mechanism, when $n_i \sim 4\times10^{12}$ cm^{-2}.

The limit of the mobility at low electron concentrations defines how fast the final carriers in the channel can be removed and consequently puts a limit on how fast a device can switch. This RC time constant is long for larger gate length devices such as those used as test structures. For the different devices the mobility level at low concentration is a measure of epitaxial quality in the GaN channel. A higher mobility value indicates better control of impurities at this layer as can been seen in the commercial device. This parameter can be used to test and compare different epitaxial quality using a fast electrical method.

IV. Conclusion

The work here presents a straightforward gate admittance based method for determining electron mobility at very low electron concentrations which is well suited to lateral GaN devices. We observe a decrease in mobility consistent with scattering from ionized donors and present a never before observed region in GaN HEMTs where mobility becomes independent of n_i. This independence indicates that there is no longer screening of charges suggesting a percolated ground state where bare coulomb potentials are the cause of scattering. This region defines a depletion rate for a device and is an important indicator of epitaxial control of impurities in the GaN channel.

References

[1] T. Ando, A. B. Fowler, and F. Stern, “Electronic properties of two-dimensional systems,” *Rev. Mod. Phys.*, vol. 54, no. 2, pp.437-672, 1982.

[2] J. S. Kang, D. K. Schroder, A. R. Alvarez, “Effective and field effect mobilities in Si MOSFETs,” *Solid-State Electronics,* vol. 32, no. 8, pp. 679, 1989.

[3] D. K. Schroder, *Semiconductor Material and Device Characterization*. New York: Wiley, 1990.

[4] M. J. Manfra, K. W. Baldwin, A. M. Sergent, and K. W. West, “Electron Mobility Exceeding 160000 cm^2/Vs in AlGaN/GaN heterostructures grown by molecular beam epitaxy,” *Appl. Phys. Lett*., vol. 85, no. 22, pp. 5394, 2004.

[5] I. P. Smorchkova, C. R. Elsass, J. P. Ibbetson, R. Vetury, B. Heying, P. Fini, E. Haus, S. P. DenBaars, J.S. Speck, and U. K. Mishra, “Polarization-induced charge and electron mobility in AlGaN/GaN heterostructures grown by plasma assisted molecular-beam epitaxy,” *J. Appl. Phys.*, vol. 86, no. 8, pp. 4520, 1999.

[6] M. J. Manfra, K. W. Baldwin, A. M. Sergent, R. J. Milnar, and J. Caissie, “Electron mobility in very low density GaN/AlGaN/GaN heterostructures,” *Appl. Phys. Lett.,* vol. 85, no. 10, pp. 1722, 2004.

[7] W. M. Waller, S. Karboyan, M. J. Uren, K. B. Lee, P. A. Houston, D. J. Wallis, I. Guiney, C. J. Humphreys, and M. Kuball, “Interface state artefact in long gate length AlGaN/GaN HEMTs,” *IEEE Trans. Electron Devices*, vol. 62, no. 8, 2015.

[8] P. D. Chow, and K. Wang, “A new AC technique for accurate determination of channel charge and mobility in very thin gate MOSFETs,” *IEEE Trans. Electron Devices,* vol. 33, no. 9, 1986.

[9] L. Ardaravicius, A. Matulionis, J. Liberis, O. Kiprijanovic, M. Ramonas, L. F. Eastman, J. R. Shealy, and A. Vertiatchikh, “Electron drift velocity in AlGaN/GaN channel at high electric fields,” *Appl. Phys. Lett.*, vol. 83, no. 19, 2003.

[10] K. Hirakawa, and H. Sakaki, “Mobility of the two-dimensional electron gas at selectively doped n-type AlGaAs/GaAs heterojunctions with controlled electron concentrations,” *Phys. Rev. B*, vol. 33, no. 2, pp. 8291, 1986.

[11] S. Takagi, A. Toriumi, M. Iwase, and H. Tango, “On the universality of inversion layer mobility in Si MOSFETs,” *IEEE Trans. Electron Devices,* vol. 41, no. 12, 1994.

[12] P. Toniutti. P. Palestri, D. Esseni, and L. Selmi, “Revised analysis of the mobility and I degredation in high-k gate stacks: surface optical phonons vs. remote Coulomb scattering,” *ESSDERC*, Edinburgh, 2008, pp. 246 – 249.

[13] A. Thongnum, and U. Pinsook, “Electron transport properties in m-plane and c-plane AlN/GaN heterostructures with interface roughness and anisotropic in plain strain scatterings,” *J. Phys. D: Appl. Phys.*, vol. 48, 2015.

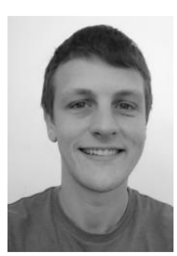
[14] M. J. Manfra, K. W. Baldwin, A. M. Sergent, R. J. Molnar, and J. Caissie, “Electron mobility in very low density GaN/AlGaN/GaN heterostructures,” *Appl. Phys. Lett.,* vol. 85, 2004.

[15] D. Jena, A. Gossard, and U. Mishra, “Dislocation scattering in a two-dimensional electron gas,” *Appl. Phys. Lett.*, vol. 76, no. 31, pp. 1707, 2000.

[16] J. Antoszewski, M. Gracy, J. M. Dell, L. Faraone, T. A. Fisher, G. Parish, Y.-F. Wu, and U. K. Mishra, “Scattering mechanisms limiting two-dimensional electron gas mobility in AlGaN/GaN modulation-doped field-effect transistors,” *J. Appl. Phys.*, vol. 87, no. 8, 2000.

[17] S. Das Sarma, E. H. Hwang, and Qiuzu Li, “Two_Dimentional metal-insulator transition as a potential fluctuation driven semiclassical transport phenomenon,” *Phys. Rev. B*, vol. 88, pp. 155310, 2013.

[18] G. Reimbold, “Modified 1/f trapping noise theory and experiments in MOS transistors biased from, weak to strong inversion,” *IEEE Trans. Electron Devices*, vol. ED-31, no. 9, 1984.



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